Procedia Engineering
Volume 143, 2016, Pages 161–169
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Damage Behavior of Cement-Treated Base Material

Korakod Nusit[1] and Peerapong Jitsangiam[1,2*]
[1]*Curtin University, Perth, Australia*
[2]*Chiang Mai University, Chiang Mai, Thailand*
korakod.nusit@postgrad.curtin.edu.au, p.jitsangiam@curtin.edu.au

Abstract
Cement treated base (CTB) is a cement stabilized material which becomes more important to a modern road pavement under a better performance perspective. However, CTB has the inherent characteristic of fatigue deterioration corresponding to damage evaluations under repeated loading; but relatively rare fatigue and damage studies of CTB have been performed. Therefore, damage developments of CTB specimens tested under different loading conditions were characterized in this study. This because stress/strain state and fatigue life of materials are all related to their damage evolutions. Results from unconfined compressive tests revealed that damage evolutions of CTB specimens depended on the monotonic-compressive loading rates. Moreover, the cyclic flexural beam tests were also performed to determine the fatigue damage evolutions of CTB specimens. The test results showed that damage evolutions of CTB specimens subjected to cyclic bending forces were influenced by the levels of applied strain. However, the damage evolutions were independent from the loading waveforms. In addition, the prediction models for damage evolutions of CTB were also developed in this study. The natural logarithmic model was found to provide the most reliable values of predicted damage variable compared to the other mathematical models used in this study. It was also discovered that regression parameters of the developed model can be estimated by the function of an applied strain level. Furthermore, this study reveals that the fatigue behavior of CTB specimens can be predicted based on the damage variables.

Keywords: Bound cement-treated base course, damage variable, fatigue damage, continuum damage mechanics

1 Introduction

Cement-treated base (CTB) is the product of soil-cement stabilization technique by mixing a conventional road base material with a prescribed amount of cement, and water. In general, cement content in a CTB mixture is considerably less than that used in concrete. Appropriate quantities of cement and water for a CTB mixture are determined based on the mix design process of CTB. In such mix design process, unconfined compressive strength (UCS) of CTB is generally specified to meet requirements of pavement structure [1,2]; subsequently, the trial-and-error process is performed with

* Corresponding author. Tel.: +61-8-9266-4527; fax: +61-9-266-2681.

Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.021

varying cement contents in a series of CTB mixtures until achieving a required UCS value at a specific cement content. Furthermore, the optimum moisture content (OMC) derived from the compaction test protocol is generally specified as a proper amount of water for a CTB mixture. CTB with a relatively high cement content and a significant UCS value can be classified as a bound (fully stabilized) material of which tension resistance reveals. At present, the bound CTB is considerably required to serve better performance road pavement with longer lifetime and less maintenance. Nevertheless, the bound CTB is a relatively stiff material which may undergo fatigue failure under traffic. Accordingly, the design lifetime of pavement structure with a bound CTB layer strongly relies on fatigue deterioration of CTB under traffic [3,4]. However, current fatigue prediction models of CTB, following any pavement design guideline, used for an estimation of a whole pavement life are empirical [5]. Therefore, it is necessary to develop a more mechanistic-based fatigue prediction model of CTB to overcome shortcomings of using those empirical-based prediction models. Continuum damage mechanics (CDM) has been successfully applied to develop mechanistic fatigue deterioration models of asphalt concrete [6] and conventional concrete material [7,8]. These models were established based on the assumption that fatigue failure is principally caused by damage evolutions within the mass of materials. Consequently, prior to establish a fatigue deterioration model of CTB, it is important to examine the characteristics of damage growths induced by various loading conditions. Therefore, this study aims to characterize damage evolutions of the bound CTB material under two loading regimes of monotonic and cyclic loading. Bound CTB specimens were performed under the testing conditions of different loading rates of monotonic-compressive loading and cyclic flexural loadings.

1.1 Current Fatigue Model of Cement-Treated Materials

Austroads [9] has recommended the equation to estimate the in-service fatigue life of a CTB layer in pavement as following:

$$N = RF\left(\frac{278FS+\frac{1070000}{E_f}-311}{\mu\varepsilon}\right)^{12} \tag{1}$$

where N is the in-service fatigue life (cycles), RF is the project reliability factor, FS is the design flexural strength (MPa), E_f is the design modulus of cemented material (MPa), and $\mu\varepsilon$ is the load-induced tensile strain at the base of the cemented material (micro-strain). The design modulus in Eq. (1) can be either obtained from the flexural beam test or the empirical equation recommended by the guideline [9]. Moreover, Eq. (1) was developed based on a series of test results of the test specimens prepared using 12 parent materials collected nationwide across Australia (accept from Northern Territory and Tasmania).

1.2 CDM for Fatigue Modelling

CDM is the discipline that quantifies the microscopic damage of a material on the macroscopic scale, using internal damage variables [10]. Consequently, damage variable (D) has generally been employed as the indicator of representing damage levels. The minimum value of D ($D = 0$) indicates that the status of a material is at the original stage without any damage; vice versa, the fully damage status of a material is specified if D attains to the maximum value of $D = 1$. Therefore, the stress-strain constitutive law with consideration of material damage [8] can be draw as follows:

$$\boldsymbol{\sigma} = (1 - D)\boldsymbol{C}:\boldsymbol{\varepsilon} \tag{2}$$

where $\boldsymbol{C}$ is the fourth-order undamaged Hooke's elasticity tensor, $\boldsymbol{\sigma}$ is the second-order stress tensor, $\boldsymbol{\varepsilon}$ is the second-order strain tensor, D is the damage variable, and the symbol of ":" represents the double tensor contraction. In the one-dimensional problem, $\boldsymbol{C}$ is equivalent to Young's modulus (E) of a material. Note that inelastic strain and time-dependent dynamic effects were excluded from the stress-strain relationship in Eq. (2). CDM was successfully applied to model the behavior of asphalt concrete under cyclic loading by [11]. This model was further developed by [12] to consider the viscoplasticity behavior in the constitutive model. For concrete material, [7] and [8] proposed three-dimensional models to predict the fatigue behavior of plain concrete under cyclic compressive loading and cyclic flexural loading, respectively.

It can be observed from Eq. (2) that D is the only additional parameter from the conventional elastic stress-strain relationship equation. Previous studies on damage evolution characterization of concrete material can be found from [13,14,15,16,17]; however, the study on damage evaluations of CTB is apparently unavailable. Therefore, this study initiatively examined damage evolutions of CTB. Testing plan to achieve the study aim is provided in the following sections.

2 Laboratory Works

Major laboratory tests in this study were unconfined compressive tests and cyclic flexural beam tests. CTB specimens in this study were manufactured from the standard crushed rock material collected from a local quarry in Perth, Western Australia. General purpose (GP) cement of 5% by dry weight of standard crushed rock were mixed with the parent material and water at OMC (derived from modified compaction test results [18]). The values of maximum dry density (MDD) and OMC obtained from modified compaction test are 2.27 g/cm^3 and 6.5%, respectively. According to [1], CTBs with cement content equal to 3% and higher are classified as the bound CTB. Unconfined compressive tests according to [19] (ASTM D1633) were performed after the test specimens attained 28 days of moist curing. The dimensions of UCS specimen employed in this study are 100 mm in diameter and 115 mm in height. It should be highlighted that the strength of a material determined from the conventional UCS test is categorized as a static parameter; but, the CTB layer in the real pavement are generally subjected to dynamic loads induced by moving vehicles. Accordingly, additional unconfined compressive tests with dynamic loading rates were conducted in this study. The loading rate conforming to the dynamic loading strain rate recommended by [20] was employed, along with the loading rate for the static tests equivalent to the value recommended by [19]. Therefore, the strain rates for the static and dynamic loadings used in this study were 1.4×10^{-4} and 1.0×10^{-3} strain per second, respectively.

Fig. 1. (a) Prismatic beam specimens; (b) cyclic flexural beam test.

For the cyclic flexural beam tests, prismatic beam specimens were tested in accordance with the standard four-point bending test protocol for asphalt concrete [21]. The CTB specimens with 5% cement content were prepared based on [22] to meet the standard beam size of 50×63.5×400 mm^3 (see Fig. 1 (a)). Fig. 1 (b) illustrates the example of the cyclic flexural beam test performed in this study. After 28 days of curing, the CTB specimens were tested under the repeated haversine and sinusoidal load waveforms with the frequency of 10 Hz. The test temperature was maintained at 20 °C throughout the tests. Strain levels varied from 75 to 200 micro-strains were applied to the test specimens under the strain-controlled testing condition. During the tests, reduction in cyclic flexural modulus values due to the fatigue damage were monitored and employed as one of the test termination condition. [21] recommended the termination condition of the cyclic flexural beam tests when reaching one million loading cycles or the value of cyclic flexural modulus decreases to one-half the initial value. According to the guideline, the initial cyclic flexural modulus is defined as the flexural modulus value at the 50th loading cycle of a full series of applied cyclic load.

3 Results and Discussions

3.1 Damage Evolutions from Monotonic Compression Tests

The stress-strain curves shown in Fig. 2 (a) were the results of unconfined compressive tests with respected to different loading strain rates. Specimens D-1, D-2, and D-3 were subjected to the dynamic loading rates during the tests, while the static loading rates were applied to specimens S-1, S-2 and S-3. The bold lines in the figures represent the average values from three replicated specimens. It can be clearly seen that both UCS and modulus of the materials were dependent to the loading strain rates. Furthermore, damage evolutions of CTB calculated from the test results were also dependent to the applied loading strain rates as demonstrated in Fig 2 (b).

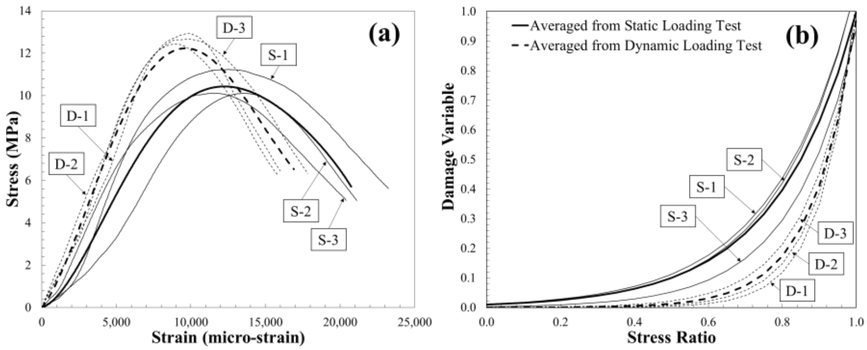

Fig. 2. (a) Stress-strain relationships; (b) damage evolutions from monotonic compressive test.

In this study, the damage variable is defined as the degradation of tangent modulus [17]. The initial tangent modulus is the secant modulus of 5% strain. Therefore, the damage variable can be estimated from Eq. (3).

$$D_n = \frac{E_n - E_i}{E_i} \tag{3}$$

where D_n is the damage variable at current applied stress, E_i is the initial tangent modulus or initial cyclic flexural modulus, and E_n is the tangent modulus at current applied stress or cyclic flexural modulus at current applied loading cycle. It can be seen that D_n calculated from Eq. (3) is equivalent to D in Eq. (2). The stress ratio in Fig. 2 (b) is the ratio between current applied stress and UCS of the CTB. Fig. 2 (b) shows that at the same stress ratio, the dynamic load creates minor damage compared to the static load. Similar behavior was also encountered from concrete materials [15,17]. However, the damage growth was dramatic and sudden for specimens subjected to dynamic loading at high stress ratios. At low stress ratios, the slow rate of damage evolutions may be the reason of higher strength and higher elastic modulus observed from specimens subjected to dynamic loading. Moreover, a sudden increase in load-induced damage at high stress ratio may be the cause of brittle failures. In summary, the results from this section demonstrate that the response of CTB are dependent to the loading rates. Applying static parameters to the pavement structural design may result in a conservative pavement section (modulus of CTB under static loading is less than that of CTB under dynamic loading). However, [23] showed that the critical tensile strain of the CTB layer in pavement structure, induced by standard axle load [3], is generally less than 150 micro-strain. Therefore, design parameters determined from the UCS test may be not suitable for pavement structural design, because the conventional UCS test usually reports only the material response within a large-strain regime (Fig. 2 (a)).

3.2 Damage Evolutions from Cyclic Flexural Beam Tests

Test results from the cyclic flexural beam tests are illustrated in Fig. 3 (a) and Table 1. Specimens F-1, F-2 and F-3 were tested under the repeated haversine loading waveform, while the repeated sinusoidal loading waveform was applied to the specimens F-4 to F-8. As shown in Fig. 3 (a), the newly defined parameter of normalized cyclic flexural modulus is the ratio between the cyclic flexural modulus at the current applied loading cycle and the initial cyclic flexural modulus. That means the maximum and minimum values of the normalized cyclic flexural modulus are one and zero, respectively. Note that the normalized cyclic flexural modulus in this study is equivalent to modulus ratio (SR_n) proposed in the fatigue extrapolation model developed by [24]. The reduction in the normalized cyclic flexural modulus values shown in Fig. 3 (a) resulted from the fatigue damages. It can be visible that the damage of CTB specimens increased with respect to an increase in a number of loading cycles. Accordingly, the damage variables (Eq. (3)) were calculated and plotted versus the normalized loading cycles ($C_n = C_i/C_m$) as shown in Fig. 3 (b); in which C_i is the current applied loading cycle, and C_m is the maximum applied loading cycle. As previously mentioned, the cyclic flexural beam tests were terminated at either one million loading cycles was completed or the cyclic flexural modulus reduced by one-half the initial value; therefore, the maximum value of damage variable in this study is 0.5.

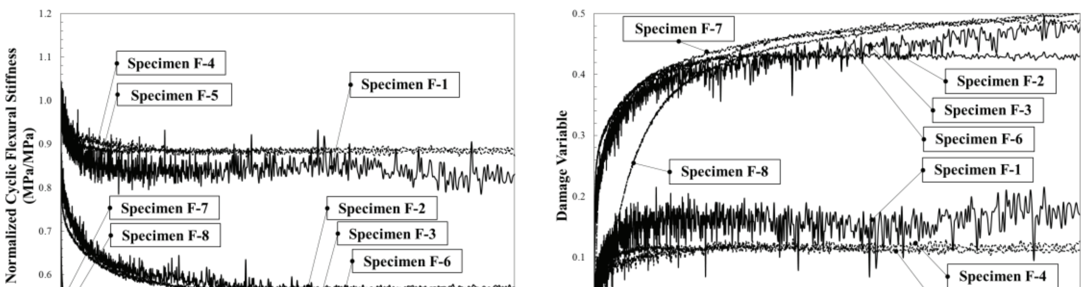

Fig. 3. (a) Results from cyclic flexural beam test; (b) damage evolutions from cyclic flexural beam tests.

According to Fig. 3 (a) and (b), it is obvious that applied strain levels greater than or equal to 150 micro-strain induced significant damage to CTB specimens, with the condition of the applied cyclic loadings less than one million cycles. Therefore, the damage variables of specimens F-2, F-3, F-6, F-7 and F-8 were approximately equal to 0.5 when the normalized applied loading cycles were close to one. In contrast, the cyclic flexural modulus of specimen F-1, F-4 and F-5 were reduced less than 20% (D_n < 0.2) by the repeated loads with the applied strain levels lower than 150 micro-strain. It should be emphasized that the damage evolutions of CTB are independent from the applied loading waveforms.

3.3 Extrapolation Methods to Predict Damage Evolutions of CTB

As discussed previously, the damage variable can be used for (1) predicting the remaining service life of road pavement, and (2) estimating the current states of applied stresses/strains (by substitute the damage variable to Eq. (2)); consequently, a reliable prediction equation to estimate the damage variables is significantly important to more advanced pavement design. Therefore, in this study, the extrapolation methods suggested in the NCHRP report no. 646 [25] were adapted to determine the damage prediction model in this study. It should be highlighted that [25] aimed to assign the fatigue life prediction models for asphalt concrete material, while the prediction model in this study was developed to estimate the damage evolutions of CTB under cyclic flexural loading. Prediction equations established from three different mathematical models were analyzed in this study. This included power model, natural logarithmic model, and Weibull survivor function developed by [24] (Tsai's model). However, coefficient of determination derived from power model (R^2) was generally lower than the values obtained from the other two models (0.61 to 0.88); therefore, only the analysis results of natural logarithmic model and Tsai's model are provided in Table 1.

Tsai's model was basically developed based on the Weibull survivor function to determine the modulus ratio from a given loading cycle. The natural logarithmic model in this study was constructed to estimate the damage variable from a given normalized applied loading cycle. In consequence, Tsai's model was used to estimate the relationships of parameters plotted in Fig. 3 (a), whilst the natural logarithmic model was used to predict the relationships of parameters shown in Fig. 3 (b). However, it can be clearly seen that R^2 values obtained from the curved fittings with the natural logarithmic model were higher than the values obtained from Tsai's model. Therefore, based on the analytical results from this study, it can be concluded that the natural logarithmic model would be more suitable for damage evolutions prediction of CTB material than that of the Tsai's model.

Specimen	Loading function	Applied strain level	Initial cyclic flexural modulus	Prediction model					
				$D_n = \alpha + \beta ln(C_n)$*			$ln(-ln(SR_n)) = ln(\lambda) + \gamma ln(C_i)$**		
		(micro-strain)	(MPa)	α	β	R^2	λ	γ	R^2
F-1	Haversine	100	20,407	0.19	0.03	0.82	0.0021	0.36	0.72
F-2	Haversine	150	14,721	0.47	0.04	0.99	0.0336	0.23	0.79
F-3	Haversine	200	22,510	0.47	0.05	0.98	0.0339	0.22	0.96
F-4	Sinusoidal	75	9,982	0.13	0.01	0.97	0.0037	0.29	0.85
F-5	Sinusoidal	100	12,308	0.13	0.01	0.87	0.0229	0.14	0.69
F-6	Sinusoidal	150	9,737	0.50	0.06	0.99	0.0245	0.25	0.95
F-7	Sinusoidal	175	11,097	0.53	0.07	0.96	0.0559	0.28	0.78
F-8	Sinusoidal	200	7,818	0.58	0.12	0.94	0.0059	0.63	0.73

Note: * Natural logarithmic model.

** Equation developed by [24].

Table 1. Cyclic flexural beam test results and damage evolution extrapolations.

3.4 Modified Damage Evolution Prediction Models

Previous section indicates that damage variables can be estimated from the natural logarithmic model (Ln model). Fig. 4 (a) presents the relationships between regression parameters of Ln model (α and β) and applied strain levels. Note that, β parameter of specimen F-8 was not included in the regression analysis. However, a more detailed examination of the Ln model could indicate the model's limitations. First, based on the Ln model expressed in Table 1, the predicted damage variables are less than one (negative value) if the absolute values of $\beta \times \ln(C_n)$ are greater than α. This contradicts to CDM theory that damage variable is always greater than or equal to zero. Therefore, the working range of Ln model is in between [$C_i > C_m \times e^{(-\alpha/\beta)}$] and [$C_i = C_m$]. For example, Ln model provides the reasonable estimation of damage variables for specimen F-6 in the case that C_i varies from 241 cycles to a million cycles. Second, in the case that Ln model from Table 1 was used to estimate the damage evolutions of specimen F-7 and F-8, the predicted damage variables went higher than 0.5 if the normalized applied loading cycles were greater than 0.65. This finding indicates that the proposed model overestimates the damage variables, which should be lower than 0.5 as discussed previously. Therefore, the model improvement was required at this stage. Two modified equations were employed in this study, namely (1) modified Ln model, and (2) polynomial-Ln model (Fig. 4 (b)). The modified Ln models of specimen F-7 and F-8 were constructed by limiting the α parameter of the original Ln model to 0.5. Accordingly, the predicted damage variables from the model are always lower than or equal to 0.5. However, the R^2 values derived from the modified Ln model are generally lower than those achieved from the original Ln models. More importantly, the modified Ln models seem to underestimate the damage variables at the greater values of normalized applied loading cycle, as shown in Fig. 4 (b). Eventually, the polynomial-Ln models of specimen F-7 and F-8 were developed to improve the precision of prediction model. Fig. 4 (b) illustrates that the polynomial-Ln models were fitted with the test results superior than the modified Ln model (higher R^2). Moreover, accurate damage variables can be also obtained from the polynomial-Ln model at the greater values of normalized applied loading cycle.

At this stage, the analysis results in this section reveal that damage evolutions of CTB specimens under cyclic flexural loading can be rationally estimated from the proposed Ln model. In addition, the reliability of the Ln model can be improved by employing the polynomial regression analysis in the model development as shown in Fig. 4 (b).

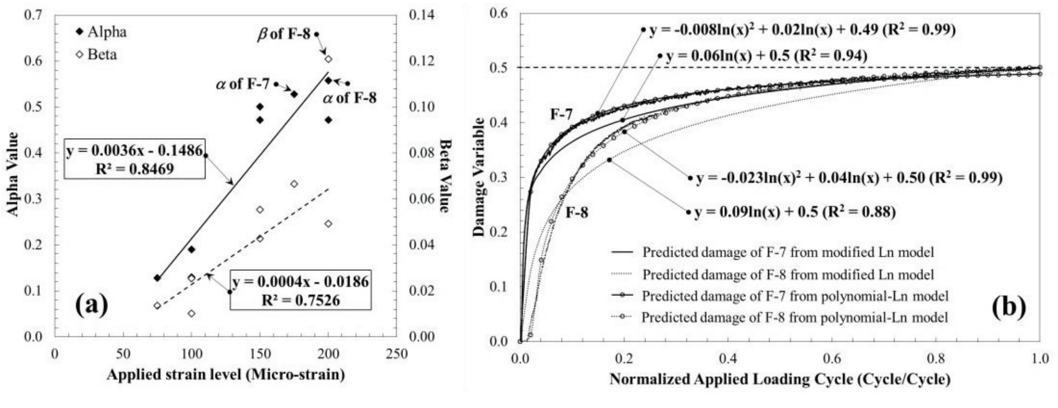

Fig. 4. (a) Relationships between regression parameters and applied strain levels; (b) modification of the prediction models.

4 Conclusion

This research aims to characterize the damage behavior of CTB through the CDM concept under different loading conditions. The test results obtained from unconfined compression tests and cyclic flexural beam tests were used to develop the damage evolution curves of CTB in this study. Damage developments of CTB under monotonic compressive loadings dependent to applied loading rates. However, unconfined compressive tests are generally performed within a range of a large-strain regime, which would not be suitable to the pavement structural design with consideration of a relatively small-strain regime. In addition, the damage evolutions of CTB material were also influenced by the applied strain levels in the cyclic flexural beam tests. Test results revealed that applied strain levels greater than or equal to 150 micro-strain could induce significant fatigue damage to the CTB specimens, with the cyclic loadings less than one million cycles. The prediction model of damage evolutions was also developed in this study. Analytical results indicated that damage evolutions of CTB can be estimated from the proposed natural logarithmic model. Therefore, the damage variable would be considered as one of the input parameters for fatigue life prediction model of CTB.

Acknowledgements

The authors wish to express their gratitude to the Australian research council (ARC) for financial support for this research, under the ARC linkage scheme (LP-130100884), conducted at the department of civil engineering, Curtin university.

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